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Short Distance Wireless BU

TEXAS INSTRUMENTS

Bluetooth *ExtraRange* Proposals

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Exhibit B

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I thank all those who came up with enhancement ideas that appear in this document, analyzed various aspects of them, and/or helped characterize their implementation complexity in current/future system architectures.
In addition to the highly appreciated ongoing contribution of Alan Gatherer's research team in Dallas, who are mentioned within the enhancement proposals they investigated, I wish to acknowledge those who helped me locally, at SDW:

Eli Dekel
Onn Haran
Alex Mostov
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1. General

1.1. Introduction

Texas Instruments wishes to offer a Bluetooth solution having **link performance** significantly superior to that specified in the Bluetooth Specification, as well as that offered by competitors.
It is believed that such differentiation, gained through substantial performance superiority, primarily in terms of **operation range**, will provide a crucial advantage over competition, particularly in extended-range link-sensitive applications such as telephony. It is of particular interest to enhance the performance of devices such as a stationary Access Point (AP) which is intended to provide various services, such as PSTN connectivity, to Bluetooth devices within an extended range. Such AP can be assumed to be less sensitive to increases in size, current consumption and cost, in comparison to most portable devices, where these are crucial.

1.2. Scope And Purpose of this Document

This document presents the results of a preliminary study regarding the possibility of offering an extended range Bluetooth solution, to be called ExtraRange, primarily for telephony applications.
A marketing questionnaire has been distributed internally in order to specify the requirements of such enhanced solution in terms of performance and complexity (through constraints such as cost and current consumption). The results of this, originally intended to be incorporated into this document, have not yet been received and analyzed. Therefore, this document presents only the proposals addressing this need, gives an idea of the extent of implementation work required for each, and lists the relevant existing IP. Additionally, it suggests performance measures which should be used as means for comparison and evaluation of enhancement proposals.
An actual work plan will be created following:

- the reception and analysis of the marketing inputs, and
- the release of this document, and the discussions that will follow among those who receive it.

The resultant work plan should provide a detailed description of the necessary implementation work, and outline a project to be executed in SDW in terms of schedule and resources.

2. Enhancement Proposals

This section outlines 11 different proposals intended to enhance performance, some of which were brought up disregarding practical considerations such as implementation complexity and cost. For each of these, various practical implications, estimations of the realization complexity, and the achievable performance enhancement are provided. Certain proposals may be implemented in combination with others, while some are suggested as substitutes for others, and therefore replace them.

2.1. Antenna Complex Beam-Forming / Diversity

<u>**Background and General Description**</u>
Anand Dabak from Alan Gatherer's research team has shown through simulations that by employing beamforming based on two antennas and complex weighting of the signals at the antenna terminals, gains **above 10dB** (statistical) may be obtained, under certain assumptions

regarding the indoor environment (including a walking pace of up to 3km/h). The use of two antennas at one end only (typically at a stationary access point), and the modification of the hopping sequence so as to create high correlation between the "up link" and "down link", enable both ends of the communications to achieve this significant enhancement in their reception. The gain achieved when communicating with a device whose frequency sequences are not modified is 3dB to 9dB lower, depending on the type of connection (HV1, HV3) and the movement pace of the remote device (assumed to be up to 3km/h). In addition, it has been shown that coexistence within an environment containing many such systems is enhanced, due to the directional nature of the BF antenna array.

Advantages

1) An access point may communicate with such modified device while communicating, within the same network, with other devices that remain Bluetooth compliant (non-enhanced devices, which use the standard BT frequency hopping sequence).
2) Provides the highest diversity gain achievable with two antennas at one end only (typically the AP).
3) Suffers less from coexisting systems and causes less interference to them.

Implications and Disadvantages

1) The hopping sequences must be modified, but will still comply with regulations.
2) The frequency sequence modification adds some complexity to the frequency hopping control mechanism, considering the need for backward compatibility.
3) The complex combining diversity algorithm, as well as the complex beam forming, require two receivers and a considerable amount of processing.

Attractiveness and Conclusions

Requires feasible modifications in the remote device (in the frequency sequence only), but adds considerable implementation complexity to the AP.
Not feasible in the current system architecture or in future variations of it, since it requires major changes, including some in the transceiver circuitry (accurate amplitude and phase assessment for the received signal at both antennas, and complex weighting for beam-forming transmission).

2.2. Antenna Switching Diversity

Background and General Description

This is a reduced-complexity version of the beam-forming proposal, which has also been simulated by Alan Gatherer's group. Here, a single receiver may be used, which is switched to the antenna found to be optimal at a given time and frequency. Preferably, this selection is performed during an extended preamble preceding the access code. The need for the complex weighting/combining is eliminated here, thus significantly reducing complexity, while providing gains in the order of **10dB** (statistical), less than 2dB lower than those achieved in the more complex scheme. Here too, modification to the hopping sequence is necessary to obtain the high correlation between the "up link" and "down link".

Advantages

1) An access point may communicate with such modified device while communicating, within the same network, with other devices that remain Bluetooth compliant (non-enhanced devices, which use the standard BT frequency hopping sequence).
2) Provides high diversity gain with two antennas at one end only (typically the AP).

Implications and Disadvantages

1) The hopping sequences must be modified, but will still comply with regulations.
2) The frequency sequence modification adds some complexity to the frequency hopping control mechanism, considering the need for backward compatibility.
3) The comparison between the reception of the two antennas requires some means of accurate RSSI measurement and storage, which currently can only be realized with analog circuitry, due to limitations of the current architecture in the accuracy and sampling periods of the RSSI.
4) Based on RSSI only, the wrong antenna might be selected in the presence of dominant interference.

Attractiveness and Conclusions

Requires feasible modifications in the remote device (in the frequency sequence only), but adds some implementation complexity to the AP.
Not feasible in the current system, but may be accommodated in a future variation of it, since it requires reasonable changes in the baseband chip and in the transceiver circuit (change in frequency sequences and FH management, extension of the preamble, control logic for the timing of the antenna switching, and some analog circuitry associated with the RSSI measurements and comparison).

2.3. Simplified Antenna Selection

Background and General Description

This is a further simplified version of antenna diversity, where the selection of the optimal antenna for a given frequency is performed based on reception failure/success, rather than on a comparison of reception levels. Here too, it is assumed that antenna selection is supported in the AP only, but serves the communications in both directions through the use of modified frequency sequences. The need for RSSI reading and storing is eliminated, and only digital indications of successful/unsuccessful reception are used. It is assumed that the 10dB gain offered by the ideal switching scheme (where both antennas are sampled before a selection is made), is necessary only when the reception quality is marginal (within a distance of 5dB from the threshold). After all, at 6dB above the BER=0.1% threshold, an additional 10dB gain is insignificant in practice. Hence, antenna switching is crucial primarily when one antenna provides a reception quality which results in packet failure, while the other one is, hopefully, able to provide the necessary improvement. The disadvantage here is, however, that this switching will be performed after a packet has already been lost.
The principle of operation is to keep a vector of N bits within the AP for each enhanced device that it is communicating with, where N is the number of hopping channels used, (the devices are enhanced by modifying their frequency sequences only). Each bit k ($1<k<N$) represents the last antenna used for the communications at frequency k. For SCO channels (typically an HV1 voice channel), once a packet is lost, the bit corresponding to its frequency is toggled, assuming that the other antenna will perform better. In such voice application (SCO), there is no accessible error indication anyway, so reception quality cannot be assessed more accurately based on digital indications only.

Advantages

1) The comparison between the reception of the two antennas is not based on RSSI measurements, and therefore the need for such circuitry and processing is eliminated.
2) Performs correct antenna selection in those cases where the interference received is dominant (which could mislead the RSSI-based switching of the previous proposal).

3) An access point may communicate with a modified device while communicating, within the same network, with other devices that remain Bluetooth compliant (non-enhanced devices, which use the standard BT frequency hopping sequence).

Implications and Disadvantages

1) The hopping sequences must be modified, but will still comply with regulations.
2) The frequency sequence modification adds some complexity to the frequency hopping control mechanism, considering the need for backward compatibility.
3) A packet is lost before the antenna assumed to be superior is selected.
4) The correlation between consecutive receptions at a certain frequency at the AP might be low, depending on the walking pace with the remote device. Consequently, the assumption as to the optimal antenna for a certain frequency may not hold valid long enough.

Attractiveness and Conclusions

The performance gain has not yet been characterized through simulations or experimentation. It is assumed to be a few dBs lower than that of the ideal switching scheme of the previous proposal (offering a 10dB gain).

Requires feasible modifications in the remote device (in the frequency sequence only), and adds little implementation complexity to the AP (RSSI readings and comparison are not required).

Not feasible in the current system, but may be accommodated in a future variation of this architecture, since it requires reasonable changes in the baseband chip and in the transceiver circuit (change in frequency sequences and FH management, and addition of control logic for the antenna switching).

2.4. Equalization Performed on Received Baseband Signal

Background and General Description

The baseband signal recovered by means of a frequency discriminator from the h=0.32 BT=0.5 GFSK signal, has inherent ISI and additive noise which is not AWGN. Mohammed Nafie, from Alan Gatherer's research team, has shown that a decision feedback equalizer (DFE) added onto to the baseband processing circuitry could enhance the performance by **over 2dB**. According to his simulations, such gain can be obtained with a sampling rate of 4MHz (4 samples per bit), a feed-forward length of 3 symbols (12 5-bit samples) and a feed-backward length of a single bit (from the output of the decision circuit).

Advantage

Over 2dB may be gained in a receiver based on digital processing of the baseband signal (referenced to a digital receiver not having a DFE). If the receivers at both ends of the communications are assumed to be based on digital signal processing, then the addition of the DFE algorithm will enhance the link in both directions (up-link and down-link).

Implications and Disadvantages

1) Requires a digital realization of the receiver. The current analog receiver does not support such enhancement.
2) The enhancement is only in terms of signal to noise performance given a certain transmission level and propagation losses, and not in signal to interference.

Attractiveness and Conclusions
2dB gain in reception sensitivity in both directions, assuming digital reception at both ends.
Not applicable in the current architecture, but should be incorporated into future digital architectures of the receiver.

2.5. Increase in Modulation Index

Background and General Description
Since the Bluetooth standard was designed to comply with regulations for unlicensed transmission worldwide, the 20dB channel bandwidth was forced to be less than 1MHz, to comply with the FCC's regulation 15.247 for frequency hopping systems operating in the 2.4GHz band. This is because the standard, although defined for a 0dBm level of transmission, was designed to support an optional higher level of 20dBm for extended range applications.
Consequently, even the lower power devices, which could comply with the FCC's 15.249 regulation for systems transmitting under 0dBm, are limited in their modulation index so as to occupy a 20dB channel bandwidth of 1MHz, which is not a requirement in 15.249.
For the lower transmission power (up to 0dBm) a higher modulation index can be used, e.g. h=0.7, thus approaching optimal FSK and enhancing performance by **over 6dB** (according to simulations). Furthermore, for BT devices operating outside the USA, where a 1MHz 20dB BW limitation does not exist, this mode of operation can be employed with a high transmission power level as well.
An asymmetrical system may also be considered, where an access point transmits to a remote device at a power level of 20dBm complying with 15.247 (GFSK with h=0.32), whereas the device transmits to the AP at a 0dBm level but with a higher modulation index.

Advantages
1) **6dB** may be gained in all receivers (both up-link and down-link), with the current structure (discriminator and adaptive data slicer) without requiring digital signal processing or any other major modifications to the current system.
2) Enhances signal to interference ratio by about **4dB** without increasing transmission power (assuming the interference is not from an enhanced device).
3) No additional circuitry is needed and no additional current consumption.

Implications and Disadvantages
1) The look-up-tables for the modulating signals need to be modified (stored in addition to those creating the h=0.32 modulation specified in the BT standard)
2) The baseband gain in the receiver needs to be reduced to optimize the performance of the adaptive data slicer. In order to support both h=0.32 and h=0.7, selection logic is needed.
3) When several such systems coexist, the chances for ACI are higher. In combination with a reduction in the number of hopping channels, this may be reduced.
4) Currently, inside the USA, this can be used only for low power devices.

Attractiveness and Conclusions
Provides a **6dB enhancement** in reception sensitivity and **4dB** in interference immunity in both directions, assuming same receiver architecture as in today's Twister.
Very attractive since the significant performance enhancement does not require extra cost or current consumption.

2.6. Reduction and Optimization of Hopping Channels

Background and General Description

Since the Bluetooth standard was designed to comply with regulations for unlicensed transmission worldwide, the number of hopping channels was defined as 79, thus complying with the American requirement of at least 75 frequencies. Consequently, with the 1MHz channel BW and channel spacing, the entire 2.4GHz spectrum is occupied by a single BT device, and in-band interference cannot be avoided.

By reducing the number of hopping channels, e.g. to 25, only a portion of the band would be occupied, thus coexisting better with other systems sharing the band.

Currently, within the USA, this would be possible only for low power devices (transmitting under 0dBm). Outside the USA, this could be implemented even in the higher power devices.

The system can dynamically adapt its frequency hopping sequence to the environment by monitoring the reception in each of the frequencies it uses, and replacing those where repetitive reception failures occur (as in *WiNGs*™).

Advantages

1) The system will perform better in the presence of repetitive interference and stationary multipath, which typically degrade the reception in a portion of the band, and not just at a single frequency at a time.
2) The potential interference caused to neighboring systems is reduced.
3) Doesn't require additional circuitry and current consumption.

Implications and Disadvantages

1) Currently, within the USA, this would be limited to lower power devices only (up to 0dBm).
2) Requires modifications to the frequency hopping management logic.
3) The transmission in not BT compliant, so both ends need to support this enhancement.

Attractiveness and Conclusions

Performance enhancement in the presence of heavy interference is significant.

The mechanism can be implemented without adding cost or current consumption.

2.7. Boosted Transmission Power in Access Point

Background and General Description

Increased transmission power helps overcome not only propagation losses but also active interference. By increasing the transmission power from a nominal value of 20dBm to 27dBm, 7dB are added to the "down-link" link budget, as well as to its interference immunity.

This would be allowed in the USA, since the FCC permits up to 30dBm of peak power (assuming an antenna gain below 6dBi). However, outside the USA, a slight reduction may be required. According to ETSI, with a transmission duty cycle of about 1/3, the peak power may exceed the 20dBm limit by only that much, resulting in limitation of 25dBm (with a 0dBi antenna).

Advantages

In applications where the "down link" is dominant (internet surfing), or where the link is asymmetric anyway (e.g., stronger interference located closer to a remote device than to its AP), the additional 7dB of transmission power are translated into a corresponding range extension.

In applications where the "up link" (e.g., handset to AP) may be enhanced by some other means (reduction in number of frequencies, increased modulation index, etc.), a symmetric behavior may be achieved anyway, ensuring similar reception quality at both ends.

Implications

1) In addition to the currently developed 20dBm power amplifier ("Comet"), a 7dB gain stage with 27dBm output power (0.5W) would have to be added with a cost lower than $2 and dc power dissipation in the order of 1W (0.25A @ Vcc=3.6Vdc).
2) The potential interference caused to neighboring systems is increased by 7dB.
3) The 27dBm transmission is not ETSI compliant (European market). However, an access point is not a mobile device likely to be carried abroad anyway. With a transmission duty cycle of 1/3 at the AP, up to 25dBm of peak power would be allowed in Europe.

Attractiveness and Conclusions

Performance gain: **guaranteed 7dB gain** in down-link signal to noise and signal to interference ratios (reception of the remote device). The up-link is not affected.
The added cost in the AP is tolerable, and there is no added cost in the remote device.

2.8. Enhanced Front End in Access Point

Background and General Description

The current realization in the Twister Bluetooth transceiver is intended to serve both stationary devices and remote devices, with their cost, size, and current consumption limitations. Consequently, the resultant receiver noise figure exceeds 7dB. This is primarily due to the high noise figure of the active image-reject mixer, whose limited dynamic range imposed the gain reduction of the LNA, thus degrading the overall noise figure.
An external front end with lower noise figure may be added to the Bluetooth transceiver, which would include an LNA and an image reject mixer of high dynamic range, thus enhancing reception sensitivity by about **4dB**. It should be noted that this 4dB enhancement assumes a negligible level of interference, which in many cases is not a valid assumption. Hence, in practice, these 4dB in the "up link" link budget are gained only on channels where the received level of interference at the AP is below the natural thermal noise.

Advantage

About **4dB** may be gained in the up-link, which can help compensate for the lower transmission power of the remote devices, assuming that the reception at the AP is not interfered by other systems causing an effective noise level above that of the natural additive thermal noise.

Implications and Disadvantages

1) External circuitry (RF CMOS chip?) must be added, which will contain both the enhanced LNA and the enhanced (preferably passive) image reject mixer. Such circuitry has not yet been developed.
2) Cost of the additional circuitry.
3) Additional current consumption for the enhanced front-end, which can be tolerated in non-battery operated devices such as an AP.
4) Signal to interference ratio is not affected, nor is the down-link performance.

Attractiveness

Performance gain: 4dB gain in up-link signal-to-noise ratios.
Requires RF design R&D and production effort. Not attractive in the near future.

2.9. Redundant SCO Transmissions (Time & Frequency Diversity)

Background and General Description

The SCO type of channel, intended primarily for voice connections, is isochronous in nature and cannot support ARQ, which could have compensated for lost packets. However, when BT BW is available (e.g. in a point to point scenario), the extra BW may be used to protect the voice data. This concept actually already exists in the BT protocol in the form of HV1 (or HV2) voice channels, where some FEC is employed. However, this is not very effective in the presence of multipath fading and interference, where the reception conditions are often such that even the access code is not detected properly.

By transmitting the same data twice or three times (using multiple HV3 channels), both frequency diversity and time diversity are gained, offering significant immunity to frequency selective multipath and interference. The time diversity is of particular importance in far-near scenarios where strong interference can cause desensitization of the receiver, which would be noticeable when trying to receive a weak signal in extended range scenarios. Since such interference could be even at non-adjacent frequencies, frequency diversity alone does not solve it. The interference is assumed to be non-continuous, which would be valid for most communication systems and even microwave ovens, so one of several consecutive retransmissions is likely to be received in the absence of it.

Using HV3 transmissions, which are uncoded, the same payload may be transmitted up to 3 times, and the voice applications (typically a cordless handset) may perform a majority decision for each payload bit (when all three transmissions are received and stored in a buffer), offering some coding gain in addition.

When the HV3 transmission is repeated 3 times, the full BW of the AP is consumed most of the time, but it can still periodically perform inquires, on the account of repeating transmissions, which will have a negligible effect on voice quality. Furthermore, if the AP received an indication that its first transmission has already been received, then the repeated transmissions can be canceled, thus saving the associated power consumption and air occupancy. Alternatively, for remote internet surfing, or other applications combining voice+data, the extra BW can then be used to transfer new data, thus increasing data throughput while providing the voice higher priority.

Advantages

1) In addition to the mitigation of multipath effects, this will yield a significant performance enhancement in the presence of interference.
2) No complexity issue (no need for antenna switching circuitry or complex processing).
3) No cost implications at all.
4) The transmission is fully down-compliant with non-enhanced devices.

Implications and Disadvantages

1) An active device would consume more power associated with the extra receptions and transmissions of packets (depending on the use of conditional retransmission based on reception acknowledgements).
2) Fewer devices could be supported simultaneously in the network since a single device could consume double or triple BW (again, depending on the use of conditional retransmissions).

Attractiveness

Not supported in the Typhoon, since only one SCO channel may be handled.

Very attractive for current system architecture (Mistral), considering the types of modifications required to support this (application level, software, simple logic).

2.10. Use of Asynchronous Link with ARQ

Background and General Description

Bluetooth's asynchronous links employing ARQ reach their maximal throughput in the absence of link errors, and their throughout is degraded as link errors increase and more retransmissions are requested. If the voice packets were to use such retransmissions, instead of being based on an SCO as defined in the BT standard, only those voice packets that are not received properly would be retransmitted, thus adapting the consumed BW to the link conditions. This provides both frequency and time diversity, as in proposal 9, while maintaining more flexibility and efficiency in the allocation of BW, which is most important for an AP serving several devices simultaneously.

In order to utilize the ACL BW efficiently, the voice should be compressed, which may be performed in the already existing DSP of a handset. This assumption may not be made for a headset, but such application is not typically an extended-range one anyway. Both ends of the communications would have to hold buffers (FIFOs) which would receive the voice data from the link at a variable rate (depending on link conditions) and would output the voice data isochronously. The size of these buffers will determine the immunity to packet failures and the resultant time delay. It is likely that such scheme will also require echo-cancellation in telephony applications due to the delays associated with the voice processing and data transfer. This too may be performed in the already existing DSP.

Advantages

1) In addition to the mitigation of multipath effects, this will yield a significant performance enhancement in the presence of interference.
2) BW is used more efficiently.
3) No additional hardware necessary to achieve the diversity.
4) Transmission is BT compliant (but not application compliant, since voice devices are typically served by SCO links).

Implications and Disadvantages

1) Not applicable in simple low-power devices where the MIPS required for the voice processing are not available (such as headsets).
2) Requires a buffer (FIFO) at both ends and management logic (currently 4Kbyte is supported).
3) Requires complex processing of voice (compression and echo cancellation).
4) Not compliant with non-enhanced devices, typically using SCO channels for voice.

Attractiveness

Efficient in terms of device current consumption and BW vs. received voice quality.
Somewhat complex in implementation.

2.11. Master-Slave Extended Dwelling

Background and General Description (copied from the text of Dabak & Panasik)

The no-ARQ scheme for voice in Bluetooth implies that voice applications cannot exploit the full frequency diversity inherent in Bluetooth. This is because the frequency hopping only makes the channel look like a fast fading channel. However, packet error rate for voice is still given by a single path Rayleigh fading (in the absence of antenna diversity). In order to improve upon this, we propose a Master-Slave Dwelling (MSD) on a frequency scheme. In this scheme, nominally the Master and Slave(s) are using the normal Bluetooth hopping frequencies. The Master does a channel measurement for each Slave and after a while communicates to that Slave to start using a single frequency for time T, instead of the normal hopping frequencies.

The time T will be less than the maximum allowed time by FCC, that a frequency hopping system can dwell on a single frequency. After time T, the Master and Slave return to normal hopping, wherein the Master does new channel measurements. This scheme would perform like a selection diversity over a number of independent Rayleigh fading channels. For typical indoor applications the number of independent channels would be between 4-5 depending upon the indoor delay spread. The Master-Slave Dwelling (MSD) is expected to give significant performance gains for voice applications involving low Doppler speeds (slower than walking speeds). The slow Doppler speed implies the channel does not vary over the channel measurement and the Master-Slave Dwell time. Currently evaluating the performance of the MSD scheme and writing the details of the scheme. (Anand Dabak, Carl Panasik)

Advantages

1) Better utilizes the frequency diversity inherent in frequency hopping by extending the dwell time of better channels.
2) No additional hardware necessary to achieve the diversity.

Implications and Disadvantages

1) There might be a problem with FCC compliance, since they demand that at least 75 hopping channels be used equally. Different dwell times are allowed as long as the total time each frequency is used within a 30 second period is equal (0.4sec in the case of 75 frequencies).
2) Requires complex frequency hopping management to be able to support such enhanced devices while supporting devices with the standard frequency sequence and dwell times.

Attractiveness

Efficient in terms of device current consumption and BW vs. received voice quality. Somewhat complex in implementation.
Requires investigation to determine the actual gain obtainable for walking pace, and to determine the FCC compliance issue.

3. Measures of Merit

This section suggests an approach of defining measures of system performance and cost effectiveness, which could be used to evaluate the merits of enhancement proposals.
The additional costs and current consumptions associated with the various enhancements cannot be compared directly, since they each result in a different performance enhancement (or range extension). It therefore makes sense to define the merit of each proposal as some ratio between the gain achieved through its realization and the sacrifice made to obtain it. The gain, in this case, should be expressed in terms of voice quality, data-throughput, data latency, range, battery life expectancy, or other user-perceived measures.
For example, if voice quality is concerned, the following measure may be defined:

1) Extra BW consumed per dB of voice quality
2) Extra current consumed per dB of voice quality
3) Extra cost per dB of voice quality

However, at this point it is believed that most proposals cannot survive the preliminary filtering based on practical constraints, such as implementation feasibility within the current system architecture. Therefore, such quantitative evaluation of each of the proposals is not done here.

4. Relevant Existing IP

This section lists various fields of IP and expertise existing within TI, which serve the purpose of implementing the proposals described in this document.

	Field of Expertise/IP	Source	Relevant to Proposals
1	Link Enhancement in the presence of multipath and active interference through combined frequency & time diversity	experience gained at SDW with the *WiNGs*™ based products	9, 10
2	Realization of high performance low cost RF circuitry (for enhanced front end design and boosted transmission power)	SDW RF Department	7, 8
3	A thorough understanding of the Bluetooth protocol and the logic and software currently implementing it	gained at SDW through the in-house design of the BT hardware and software	2, 3, 5, 6, 9, 10, 11
4	Algorithms for optimal equalization, complex antenna diversity and beam-forming	Extensive work on these topics within Alan Gatherer's research team	1, 4

5. Summary

The document presented various proposals intended to achieve an extended range for our Bluetooth systems, which was defined as a strategic goal for SDW.
The obtainable gain of each, and its realization implications in current and future system architectures, were discussed.

Some major claims of this document are:

1) Diversity gain is significantly higher than the "coding gain" achieved using HV1's and HV2's FECs (Proposals 1, 2, 3, 9, 10, 11).
2) Time diversity is most helpful in receiver desensitization scenarios (far-near coexistence scenarios), which cannot be modeled as narrow-band interference, as commonly assumed in collision simulations (Proposals 9, 10).
3) Both the reception sensitivity and the transmission power specified for our system were intended to comply with the BT standard or exceed its expectations, but may be stretched some more while still complying with regulations (Proposals 4, 7, 8).
4) Other parameters of the transmission may also be modified (modulation and frequency sequences), which in some cases would limit the operation to outside the USA due to FCC regulations regarding transmission above 0dBm (Proposals 5, 6).
5) Different enhancement schemes may be employed for the AP and the portable unit, each considering the constraints of the device they are incorporated into (Proposals 1,2,3,5,6,7,8).
6) In extended range applications, when interference is present, the link is typically asymmetrical, calling for different performance enhancement needs in the two directions (Proposals 3,5,6,7,8).
7) In certain applications, such as internet surfing, one direction may be more important than the other, which justifies unequal link budgets for the up-link and down-link (Proposals 5,6,7,8).
8) Interference and multipath can degrade the reception in a **portion of the band** for an **extended period of time**, and not just at a single frequency at a time. Therefore, the reduction in the number of channels, and the optimized selection of them provide an effective means for performance enhancement (Proposal 6).
9) The merits of the various proposals cannot easily be compared with each other since this requires considering different types of link performance enhancements (and for various scenarios) and different sacrifices (cost, current consumption, and bandwidth).

6. Conclusions

The proposals, which may be addressed in the nearer future, since they do not require major architectural modifications, are:

1) Boosted transmission power in access point (Proposal 7)
2) Redundant SCO transmissions for time & frequency diversity (Proposal 9)
3) Increase in modulation index (Proposal 5)
4) Reduction and optimization of hopping channels (Proposal 6)
5) Simplified antenna selection (Proposal 3)

The table below summarizes some of the advantages and implications of all 11 proposals:

	proposal	down-link performance enhancement (remote rec.)	up-link performance enhancement (AP reception)	additional cost and/or device current consumption	feasibility in current/future architecture
1	Antenna complex beam-forming/diversity (1)	~12dB in C/N and C/I	~12dB in C/N only	DSP	Not feasible in the near future. Requires complex processing.
2	Antenna switching diversity (1)	~10dB in C/N and C/I	~10dB in C/N only	~$1 in AP no change in device	Feasible now
3	Simplified antenna diversity (2)	Improves both C/N and C/I	Improves both C/N and C/I	"Comet" in AP must support diversity	Feasible now
4	Equalization performed on baseband signal	2dB in C/N	2dB in C/N	digital receivers	Not feasible in current analog receiver
5	Increase in modulation index	6dB in C/N and 4dB in C/I (5)	6dB in C/N and 4dB in C/I (5)	0	LUT and logic modification in current system
6	Reduction and optimization of hopping channels (3)	Substantial interference avoidance	Substantial interference avoidance	0	modification in current system
7	Boosted transmission power in access point (25dBm or 27dBm)	5-7dB in C/N and in C/I	0	$2 in AP only	Feasible now and simple to implement
8	Enhanced front-end receiver	0	4dB in C/N only	$? in AP only	R&D effort to design enhanced front-end
9	Redundant SCO transmissions (time & frequency diversity)	Most effective interference avoidance	Most effective interference avoidance	No added cost. BW and current sacrificed. (4)	Feasible now and simple to implement
10	Use of asynchronous link with ARQ	Most effective interference avoidance	Most effective interference avoidance	compression and FIFO management	Feasible in current system but complex
11	Master-slave extended dwelling (3)	Currently being investigated in Dallas	Currently being investigated in Dallas	FH management more complex at device too	current system does not support channel assessment

(1) Based on RSSI measurements, without indication of packet validity (weighting calculation is made prior to packet reception).
(2) Based on data validity indications only, and therefore detects interference scenarios too.
(3) Currently, this may not be implemented in high power devices within the USA, due to FCC limitations.
(4) Depending on the realization of conditional retransmissions and the amount of interference suffered.
(5) Assuming the co-channel interferer is not an enhanced BT device.